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UNDERLUMINOSITY AND MAGNETIC FIELDS IN BETA LYRAE

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Summary

A combination of available observational data for β Lyrae and theoretical models of evolution in close binary systems is used to show that the minimum underluminosity of the dark secondary component of this system is 1 to 4 mag. It is demonstrated that magnetic fields are probably relatively weak in massive main-sequence stars, including the two stellar components of β Lyrae, and therefore that a strong magnetic field is not a likely explanation for the underluminosity of the secondary component of β Lyrae.

Recent models of the secondary component of β Lyrae involve an underluminous star embedded in a gaseous cloud, disk, or ring.[1-5] The purpose of this letter is to estimate quantitatively the amount of underluminosity of the secondary and to show that magnetic fields do not provide a likely explanation for this underluminosity.

The mass function of the system, f(M) = 8.5, is well determined,[6] and, almost certainly, the orbital inclination lies in the range $i = 70°$ to $90°$. The mass ratio can be determined if various spectral features are associated with the dark secondary; thus $M_1/M_2 = 0.40$ by using certain broad emissions,[6] 0.17 by using the emission "peaks",[6] and 0.59 by using a faint Ca II absorption line.[7] The γ velocity derived from the faint Ca II absorption line agrees with that derived from the absorption lines of the primary, but the emission "peaks" have a γ velocity about 130 km/s too positive. Further observations are obviously needed to clear up the origin of the different lines. The early use by Kopal[8] of the ellipticity and rotational effects in the primary yielded $M_1/M_2 = 1.3$, but recent use of two variants of his first method, with better data, has yielded 0.2 – 0.5[2,9] and 0.17.[3] Unfortunately, this method is extremely sensitive to the (uncertain) effective temperature of the primary. Devinney[4] recently obtained $M_1/M_2 \leq 0.5$ from detailed comparison of the observed light curve with a set of theoretical light curves. Kuiper[10] and Abt <u>et al.</u>[11] used a group distance modulus for β Lyrae (see below) together with conventional assumptions about the mass-luminosity law for the primary and secondary[10] and for the primary (alone),[11] finding $M_1/M_2 = 1.5$ and 0.5, respectively. The modern data strongly suggest that M_1/M_2 lies in the range $0.17 - 0.59$. Huang[2] has shown, in this case, that a serious discrepancy[12] is avoided between the observed rotational velocity of the primary and the expected value based on the assumption of synchronization between axial rotation and orbital revolution.

The hydrogen lines of the primary appear to be those of a bright B9 giant ($M_v = -2$ to -5).[13] β Lyrae also happens to be the brightest member of the visual multiple system ADS 11745, of which Stars B and F are probably comoving with β Lyrae. For the primary of β Lyrae, Kuiper[10] inferred $M_v = -4.5 \pm 1$ from an old spectroscopic absolute magnitude for Star B, while Boyarchuk[14] obtained -2.7 by using the equivalent widths of Hγ and Hε in the latter star. More recently, Abt *et al.*[11] have used the full color-magnitude diagram for ADS 11745 to obtain -3.8 for the primary. A value much in excess of -4 is possibly excluded by the absence of a noticeable galactic-rotation effect in the observed space motion of β Lyrae,[10] as well as by its slightly reddened colors and by the presence of only a single sharp interstellar absorption line in its spectrum[3] (however its galactic latitude is +15°).

On the basis of the eclipse light curve, color changes during eclipse, and the weakness or absence of the spectrum of the secondary, the luminosity ratio of the components has been variously determined as $L_2/L_1 = 0.14$,[8] $0.15 - 0.26$,[15] and $0.15 - 0.28$.[16] If the faint Ca II absorption line (expected to be present in the secondary on the basis of its inferred A or F spectral type[8, 13, 16]) or any of the emission lines belongs to the central star of the secondary, the quoted values of L_2 could be attributed to the central star. However, L_2 may be due to other sources, which include the impact of gas streams on the secondary, gravitational collapse and infall of the circulating disk, or reflected light of the primary. It seems reasonable, therefore, to adopt as a limit $L_2/L_1 \leq 0.15$ for the central star.

Since M_1/M_2 and L_1 are very uncertain, a specific model of the evolutionary history of the system is needed in order to proceed further. For reasons given elsewhere,[2, 3, 5] I have adopted Huang's model, in which the primary was once the more massive member of the system and so evolved first, filling up its Roche lobe and then losing most of its envelope to its companion on a "rapid" time scale. At present, a transition to a "slow" phase of mass transfer is taking place. The large observed radius of the primary ($13 - 40\ R_\odot$ if $M_1/M_2 = 0.2 - 0.6$[2, 3, 7, 11]) indicates that this component cannot be evolving in a completely mixed state.[14] Rather, it and the drastic hydrogen deficiency require an explanation in terms of heavy mass transfer following the termination of normal core hydrogen burning in the primary.

Four theoretical studies of evolution in massive binary systems have recently been published for the case where the primary loses its envelope after the termination of core hydrogen burning.[17-20] In each investigation the initial chemical composition was $(X_e, Z_e) = (0.602, 0.044)$; the orbit was assumed to be circular and orbital angular momentum was conserved; and the secondary was assumed to accrete instantaneously all of the transferred matter and to mix completely. For each of these models, Table I gives: the masses of the components

Table 1 Four Theoretical Models of Evolution in a Close Binary System Compared with Three Orbital Solutions for β Lyrae

System	$M_1 + M_2$ ($M_\odot$)	X_1	X_2	Period (days)	Separation ($R_\odot$)
Model[17]	9 + 3.1 → 2 + 10.1	0.23	0.59	14	56
Model[18]	16 + 10.7 → 4 + 22.7	....	....	>11	>62
Model[19]	25 + 15 → 8.5 + 31.5	0.54	0.59	20	106
Model[20]	30 + 10 → 12 + 28	0.42	0.55	18	97
β Lyr[6]	$M_1 + M_2$ → 2 + 11.5	~0.15	....	13	55
β Lyr[6]	$M_1 + M_2$ → 7 + 17	~0.15	....	13	67
β Lyr[7]	$M_1 + M_2$ → 13 + 22	~0.15	....	13	76

before and after the mass exchange; the final surface hydrogen abundances; and the final orbital period and separation. For comparison, the three orbit solutions for β Lyrae[6,7] are also given, with an indication of the observed hydrogen abundance of the primary.[14,21] Notice the similarity of the first and third orbit solutions to the first and fourth theoretical models, respectively.

During the "slow" phase of mass transfer, the primary possesses a luminosity nearly equal to that of a pure-helium star of the same mass (although the primary's effective temperature is cooler on account of the presence of a residual hydrogen envelope). The secondary experiences an increase of mass without a significant increase in its fractional helium abundance, and it is still a "main-sequence" star. The expected luminosities of the two components of β Lyrae can be calculated, on this model, as a function of M_1/M_2, by using published theoretical models of pure-helium stars[22] and of normal main-sequence stars.[23] Table 2 presents final results for the expected underluminosity of the secondary (in the last column) based on the quantities: $f(M) = 8.5$; $\sin i = 1$; B. C. = -0.5 for a B9 primary;[24] and $L_2/L_1 = 0.15$. If L_2 is smaller than $0.15\ L_1$, or if the primary is still evolving in the faint "rapid" phase of mass loss, the underluminosity of the secondary will be greater than listed; or, if a significant amount of mass is still in the opaque

Table 2 Minimum Underluminosity of the Secondary Component of β Lyrae

M_1/M_2	$M_1/M_\odot$	$M_2/M_\odot$	$(M_v)_1$	$\delta(M_{bol})_2$
0.10	1	10	- 0.7	+5.9
0.17	2	11.5	- 3.2	+3.8
0.40	7	17	- 6.8	+1.4
0.59	13	22	- 8.1	+0.8
1.00	34	34	- 9.8	+0.2
1.50	80	53	-11.1	-0.1

disk,[2,3] the underluminosity will be smaller than listed. Fortunately, the numbers in Table 2 do not depend on how much mass has been lost from the system — a process that is still going on as is evidenced by the expanding shell around the system.[12]

The minimum underluminosity of the secondary component, based on the most reliable mass ratios, appears to be 1 to 4 mag. A large value is tentatively favored by the probably low luminosity and low hydrogen abundance of the primary, but a small value is favored by the two most consistent of the three orbital values of M_1/M_2.

The underluminosity of the secondary has been explained in a variety of ways,[1-5, 8, 10, 25, 26] but the criticisms made by Woolf[3] and by Stothers and Lucy[5] suggest that the most likely explanation will involve either a faint main-sequence star embedded in a massive disk[2, 3] or a rapidly rotating, massive "main-sequence" star embedded in a disk of relatively small mass.[5] It should be remarked that a massive collapsed star inside the disk is another possibility if the components have suffered a heavy mass exchange twice,[5] but this is not the reason advanced by the original proponents of a collapsed star, who supposed it to have evolved independently of the primary.[1, 4, 26, 27]

A last possibility for explaining the underluminosity is a strong interior magnetic field (see, for example, the models of Trasco[28]). Mass exchange in a close binary system uncovers inner regions of the primary star that formerly lay within the convective core and might be expected to contain a strong magnetic field.[29] The mass of the remnant is typically about one-third of the original mass, and the original gas pressure at the relevant layer of mass is $\sim 10^{16}$ dyne/cm^2. If the magnetic energy is so large as to be in equipartition with the gas kinetic energy, the magnetic field intensity will be $H \sim 6 \times 10^8$ gauss, but flux conservation during the radius expansion following the loss of the outer two-thirds of the mass will reduce this to $\sim 6 \times 10^6$ gauss. Line widths observed in the exposed remnants of β Lyrae and V356 Sgr suggest that $H < 10^5$ gauss, but most of the broadening is probably due to rotation.

Although spotty surface magnetic fields decay faster than the very slowly decaying[29] large-scale interior fields, Babcock[30] has emphasized that the surface fields in known magnetic stars appear to be coherent, and so the lifetime of these fields should be appreciable even without the presence of a regenerative mechanism. Moreover, stellar atmospheres apparently can possess magnetic fields whose energy density is several orders of magnitude greater than the local gas energy density, e.g. in the Ap star HD 215441 ($H \sim 3 \times 10^4$ gauss) and in the M supergiant VV Cep ($H \sim 2 \times 10^3$ gauss).[30] One infers from all of this that the interior magnetic field in upper main-sequence stars is probably quite weak. This is in accord with purely theoretical ideas.[31]

Nevertheless, the magnetic field, such as it is, will be carried along by the highly ionized gas streaming away from the primary in β Lyrae, and therefore may permeate the whole system, although it will be concentrated between the two components. This could account for the observed (and probably nonthermal) radio emission of the system,[32] and would suggest looking for shallow radio eclipses and for radio flaring at the surface of the primary. It is likely that the gas density in the stream (at least during the "rapid" phase of mass transfer) is fairly high, so that the combined thermal and turbulent energies of the gas remain larger than the magnetic energy. In that case, the transferring matter will not be constrained by the magnetic field to a slow rotation synchronous with the orbital revolution,[33] but will, upon accretion by the secondary, accelerate the rotation of the secondary tremendously.[3, 5, 34] This is apparently confirmed by the great breadth of the emission lines originating in the disk. Finally, it seems unlikely that the accretion process will, as a result of the convective motions, build up a strong internal magnetic field in the central star (even with the help of the seed field) since no strong field seems to be built up during the convective stages of the original star.

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